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ORIGINAL SCIENTIFIC PAPER

Step by step daily management of short-term mechanical circulatory support for cardiogenic shock in adults in the intensive cardiac care unit: a clinical consensus statement of the Association for Acute CardioVascular Care of the European Society of Cardiology SC, the European Society of Intensive Care Medicine, the European branch of the Extracorporeal Life Support Organization, and the European Association for Cardio-Thoracic Surgery

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The use of mechanical circulatory support using percutaneous ventricular assist devices (pVAD) has increased rapidly during the last decade without substantial new evidence for their effect on outcome. In addition, many gaps in knowledge still exist such as timing and duration of support, haemodynamic monitoring, management of complications, concomitant medical therapy, and weaning protocols. This clinical consensus statement summarizes the consensus of an expert panel of the Association for Acute CardioVascular Care, European Society of Intensive Care Medicine, European Extracorporeal Life Support Organization, and European Association for Cardio-Thoracic Surgery. It provides practical advice regarding the management of patients managed with pVAD in the intensive care unit based on existing evidence and consensus on best current practice.

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Keywords Mechanical circulatory support • Cardiogenic shock • Association for Acute CardioVascular Care • European Society of Intensive Care Medicine • Extracorporeal Life Support Organization • European Association for Cardio-Thoracic Surgery

Introduction

Cardiogenic shock (CS) is typically a consequence of an abrupt decrease in cardiac output causing tissue hypoperfusion, inadequate oxygen delivery, and organ failure. Death may occur early after presentation, and mortality remains high.[1,2] Mechanical circulatory support using temporary percutaneous ventricular assist devices (pVAD) that can fully or partially restore flow seems intuitively beneficial for restoring organ perfusion. This can be achieved using several mechanical support systems, most frequently veno-arterial extracorporeal membrane oxygenation (V-A ECMO) and axial flow pumps (AFPs), whereas the use of intra-aortic balloon pump (IABP) is decreasing especially in Europe after the publication of the IABP-SHOCK II trial.[3–5] The evidence for general use of these invasive and cost intensive devices is based on expert consensus, conflicting retrospective studies, and small underpowered randomized trials. The to date largest randomized trial in pVAD in cardiogenic shock outside cardiac arrest was neutral,[6] and results of ongoing trials are eagerly awaited.[7,8] Given the risk of severe complications, it is important to optimize patient selection and the management of pVAD patients in the intensive care unit (ICU). The scope of this clinical consensus statement is to review the current available evidence on the daily management of short-term mechanical circulatory support and provide practical advice. This advice is based on evidence when available or based on consensus of the writing group.

Indications

The V-A ECMO and AFPs (Impella® devices) may be used as a short-term organ support in Society for Cardiovascular Angiography & Interventions (SCAI) class C, D, and E shock with a potentially reversible underlying cause or in patients who are potential transplant or durable ventricular assist device candidates,[9] *Figure 1*. In case of refractory cardiac arrest, SCAI class E shock and in cases with combined hypoperfusion and respiratory insufficiency V-A ECMO is often favoured.[9] In acute myocardial infarction, CS with predominant left ventricular failure AFP may be preferred based on unloading effect of this device. In non-ischaemic decongested heart failure with hypoperfusion requiring inotropes, potential reversibility of the condition and candidacy for transplant or durable VAD should be discussed before initiation of pVAD. The final decision of initiation of pVAD should be made ideally by a dedicated 'Shock Team', as shown by multiple retrospective registries,[10,11] based not solely on thresholds of haemodynamic variables but also on clinical presentation, evaluation of comorbidities, frailty, and patient wishes. Most frequent contraindications to pVAD is summaised Supplemtal Appedix Table 1.

Cannulation for veno-arterial extracorporeal membrane oxygenation and implantation of axial flow pump

Careful placement of large lumen cannulas to access the devices to the patient is crucial to avoid limb ischaemia and bleeding complications. A suitable aorto-iliac-femoral arterial axis is required for femoral implantation of pVAD. If possible, a femoral angiography will aid this, but ultrasound is essential in ensuring safe puncture of the common femoral artery and vein. Well-trained staff should be ready in the catheterization laboratory and able to prepare and prime the system in case of emergency. With experience, V-A ECMO cannulation can be done

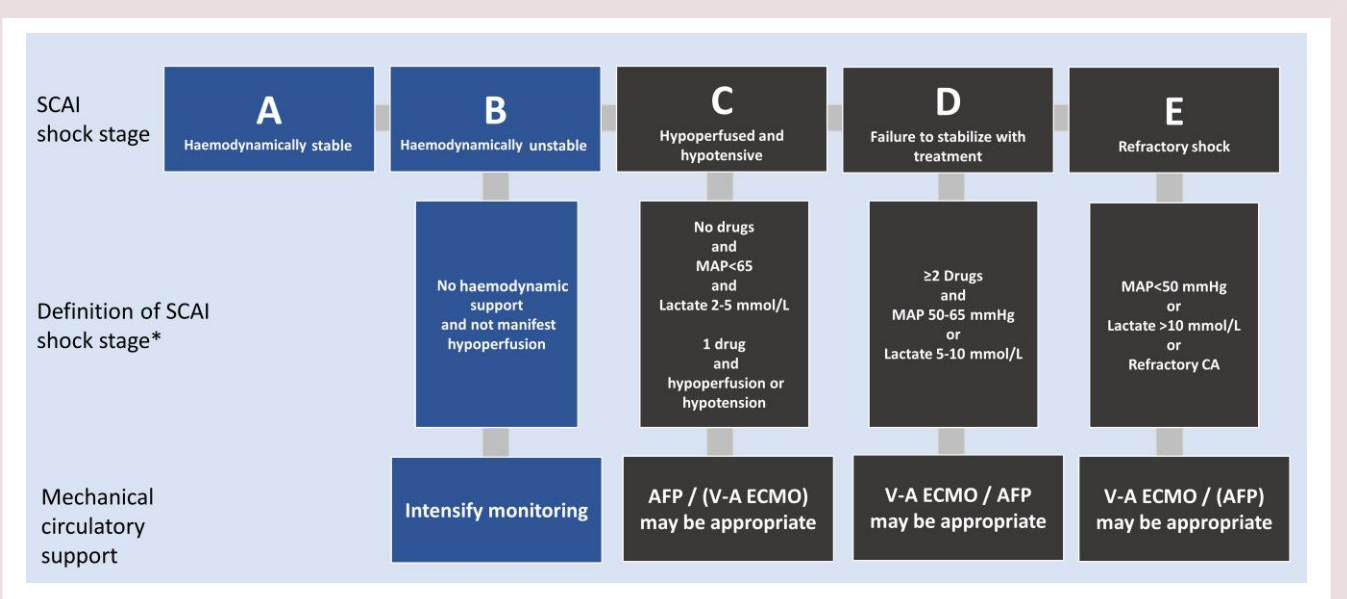
SCAI shock stage
A
Haemodynamically stable
B
Haemodynamically unstable
C
Hypoperfused and hypotensive
D
Failure to stabilize with treatment
E
Refractory shock
Definition of SCAI shock stage*
No haemodynamic support and not manifest hypoperfusion
No drugs and MAP<65 and Lactate 2-5 mmol/L
1 drug and hypoperfusion or hypotension
≥2 Drugs and MAP 50-65 mmHg or Lactate 5-10 mmol/L
MAP<50 mmHg or Lactate >10 mmol/L or Refractory CA
Mechanical circulatory support
Intensify monitoring
AFP / (V-A ECMO) may be appropriate
V-A ECMO / AFP may be appropriate
V-A ECMO / (AFP) may be appropriate

Figure 1 Proposed overview of selection of patients to percutaneous ventricular assist devices (pVAD) based on Society for Cardiovascular Angiography & Interventions (SCAI) shock classes A–E. See text for details.*The proposed haemodynamic threshold is not absolute but guiding. AFP, axial flow pump; MAP, mean arterial pressure; SCAI, Society for Cardiovascular Angiography & Interventions; V-A ECMO, veno-arterial extracorporeal membrane oxygenation; pVAD, percutaneous ventricular assist devices.

Table 1 Variables to monitor in patients on pVAD and advised general treatment targets

	Variable	Interpretation and treatment goal
Blood gas analyses		
	SVO_2 SAO_2	>55% 93–98%
	Arterial lactate	<2.0 mmol/L or decreasing
	pH	7.36–7.44
	Haematocrit	>0.24
Arterial line		
	MAP	60–65 mmHg
	Pulse pressure	>10 mmHg during V-A ECMO support. The loss of pulsatility (arterial–ventricular decoupling) can be accepted with axial flow pump if there are stable haemodynamics and lactate.
Echocardiography		
	Ventricular volumes	An increase of LV end-diastolic volume suggests an increased afterload with V-A ECMO, and RV dilatation suggests right heart failure.
	LV thrombus	The presence of LV thrombus should be ruled out.
	LVEF	Measure of global LV function can be misleading during axial flow pump support.
	LVOT VTI	Measure of native heart stroke volume
	Tissue Doppler	Lateral mitral annulus measure of LV systolic (S wave) and diastolic function (Ea wave)-RV basal free wall measure of RV systolic function (S wave)
	TAPSE	Measure of RV function (not reliable after open heart surgery)
	Aortic valve	Aortic valve opening and aortic regurgitation
	Mitral valve	Filling pressures/mitral regurgitation (information on adequate decongestion/LV unloading)
Pulmonary artery catheter		
	CVP	Measure of volume status, general target 10–12 mmHg
	PAP	Pulmonary artery pressures
	PAOP	Measure of LV end-diastolic pressure target <17 mmHg. During MCS, it can provide information on adequate LV decongestion and unloading.
	Cardiac output	In V-A ECMO, it measures native heart output; its reliability has been questioned (thermal dye loss), in patients supported by left-sided axial flow pump as a measure of total cardiac output.
	PAPi	Index of RV function calculated as pulmonary pulse pressure divided by CVP, value <1 suggests severe RV failure
	CVP/PAOP ratio	The ratio will increase with RV failure (target to <0.6).
Other		
Renal	Urine output	Renal function (target to >0.5 mL/kg/h)
Near infrared spectroscopy	Regional oxy Hb saturation	Regional lower extremity perfusion and forehead (brain) target >60%

CVP, central venous pressure; LV, left ventricular; LVEF, left ventricular ejection fraction; MAP, mean arterial pressure; PAD, pulmonary artery diastolic pressure; PAP, pulmonary artery pressure; PAPi, pulmonary artery pulsatility index; PAOP, pulmonary artery occlusion pressure; RV, right ventricular; SVO_2, central venous saturation; SAO_2, arterial saturation; TAPSE, tricuspid annular plane systolic excursion.

anywhere even in the pre-hospital setting. A detailed guide to implantation of the devices can be found in the Supplementary material online, *Appendix*. Simultaneously with placement of arterial cannula, a distal limb cannula should be placed to avoid limb ischaemia. This can either be done ultrasound-guided or surgically.

Monitoring

The intensity and degree of invasiveness of monitoring should depend on the severity and degree of instability of shock, the underlying aetiology, the comorbidities, and the patient's metabolic profile. Basic monitoring is advised to include serial assessment of lactate from blood gas analyses and monitoring of mixed venous or central venous blood saturation (SVO_2) and urine output. This requires an arterial line and a central venous catheter as a minimum. The arterial line should be placed in the right arm in patients on V-A ECMO to be able to identify differential hypoxaemia.[12] Immediate comprehensive echocardiography is advised to confirm the aetiology of shock and determine the mechanisms of cardiac output limitation as well as define potential choice of pVAD. During the V-A ECMO run, daily echocardiography is advised to evaluate left ventricular (LV) emptying, signs of LV thrombus, and recovery of native heart function. For AFP, daily echocardiography should confirm the correct placement of the device, LV and right ventricular (RV) functions, aortic regurgitation, and volume status.

Echocardiography should be repeated acutely in case of new haemodynamic instability. Early placement of pulmonary artery catheterisation is advised to guide device settings, identify potential need for escalation and venting, and evaluate signs of myocardial recovery, *Table 1*.[13] Peripheral temperature and near infrared spectroscopy of the forebrain and lower extremities may also be appropriate. Finally, advanced invasive haemodynamic assessment is advised to assess candidacy for transition to durable mechanical circulatory support and heart transplantation.

Pharmacological therapy

Analgesia and sedation

During pVAD support, sedation is a balance between potential advantages of sedation (decrease in oxygen consumption, minimize risks associated with excessive limb movement, and agitation) and its disadvantages (limited assessment of neurologic function, absence of ambulation, deconditioning, and intrinsic haemodynamic effects of the agents). Whenever possible, minimization of sedation should be prioritized while preserving patient safety and comfort. Optimal drug dosage is particularly difficult to predict during pVAD support.[14] The pVAD circuit, especially in ECMO membrane oxygenator, may promote drug sequestration. This is expected to be higher in drugs with high lipophilicity (e.g. dexmedetomidine, fentanyl, midazolam, or propofol) than hydrophilic drugs. Accordingly, higher loading and maintenance infusion doses may be required.

Inotropes and vasopressors

The use of inotropes and/or vasopressors is often unavoidable in CS, even during support by pVAD.[15] While it seems logical to limit the use of inotropes, especially in patients with underlying coronary artery disease, these drugs may still be required when attempting to limit LV distension during V-A ECMO or to support the RV with AFP. Randomized data showing any evidence for use of inotropes and vasopressors are limited and in most patients on pVAD are lacking. Dobutamine as inotrope may be appropriate given its short half-life, but phosphodiesterase inhibitors can, despite longer half-life, also be considered, and no difference in outcome was observed in a direct comparison of dobutamine and milrinone in patients without pVAD.[16] Levosimendan should not be used as a first-line drug due to long half-life, *Table 2* and non-sufficient evidence with regard to outcome in CS. Multiorgan failure and pVAD use are often associated with a decrease in vascular resistance, and vasopressors are thus used to optimize perfusion pressure to vital organs, mainly the brain, the heart, and the kidneys. The optimal perfusion pressure target during pVAD is uncertain. Evidence from observational trials is often confounded by the severity of disease, and a recent randomized trial in cardiac arrest failed to demonstrate the difference in double-blinded randomization to mean arterial pressure 63 or 77 mmHg.[27] Thus, individualization of arterial pressure based on perfusion indices may be appropriate, as in sepsis.[28]

Norepinephrine is advised as a first-line vasopressor.[19] Epinephrine and dopamine should not be used first line due to risk of tachycardia, increased aerobic glycolysis (epinephrine), and may be associated with poorer outcomes in CS.[23,24] However, this has never been investigated in patients on pVAD where vasoplegia may be excessive. In patients with capillary leak, vasopressin derivatives may be appropriate, but it should be used with caution in patients at risk of peripheral vasoconstriction or impaired splanchnic perfusion.[26] There are no available data on the use of angiotensin II in patients supported by tMCS.

Anticoagulation

Unfractionated heparin is advised for anticoagulation[29] usually guided by activated partial thromboplastin clotting time (APTT) (*Table 2*). The intensity of anticoagulation should always depend on thrombotic and bleeding risks. None of the tests can be considered as the reference standard.[30,31] The combination of APTT and anti-X_a may be appropriate in selected cases.[30,31]

Argatroban is a direct thrombin inhibitor, and its use may be appropriate as an alternative to heparin in particular in patients with heparin-induced thrombocytopaenia but based on retrospective data.[32] In Impella® supported patients, using sodium bicarbonate (25 mEq/L) in the purge solution may be an alternative to unfractionated heparin in patients with high bleeding risk.

Antibiotics

At implantation, prophylactic antibiotics may be used, but further routine use is not advised unless signs of bacterial infection emerge. During longer pVAD support, patients often become septic and require antibiotic administration. Several reports have demonstrated an increase in distribution volume and in antibiotic clearance, similarly to what has been observed in sepsis, albeit without further affecting drug dosage.[33,34]

Right ventricular support and right and left ventricular interaction

Where biventricular dysfunction is common in CS, predominantly, RV shock is uncommon, and in acute myocardial infarction CS, seen in <10% of cases.[35] The V-A ECMO provides indirect support to the RV by reducing preload, reducing RV wall tension, and delivering oxygenated blood to the coronary circulation, which may lead to improved RV function even within the first 24 h of treatment.[36] However, caution should be made when pump flow is increased. Though there is a progressive unloading of the RV, there may be a parallel increase in LV afterload caused by retrograde arterial flow resulting in increases in LV, left atrial, and pulmonary artery pressures. These changes may lead to an increase in RV afterload and a narrowing and right/upward shift of the LV pressure–volume loop.

In selected cases of isolated acute RV CS, AFP designed to support RV failure may be appropriate.[37]

Respiratory failure

Respiratory failure in CS is common, and more than 80% of patients require respiratory support.[38,39] Hypoxia will develop due to cardiogenic pulmonary oedema due to LV dysfunction[39] that impairs ventilation and increases work of breathing and thus increases oxygen consumption.[40]

Contemporary evidence advice that CS patients may benefit from positive pressure ventilation (PPV), by reducing alveolo-interstitial oedema, alveolar recruitment, and improved gas exchanges. The fraction of inspired oxygen should be titrated to a goal of SaO_2 93–98%.[41–43] In the ICU, PPV is performed as non-invasive (NIV) and invasive mechanical ventilation (IMV). While NIV is an important modality of acute cardiogenic pulmonary oedema management, it has a limited role in refractory CS requiring pVAD, and IMV is advised. A *post hoc* analysis from the TRIUMPH trial[44] highlighted that a delay in IMV initiation was associated with a higher 30-day mortality, advocating for early intubation.[45] No data support the superiority of any specific ventilation mode. Most patients receiving V-A ECMO for CS also require IMV. Although V-A ECMO may provide supplementary tissue oxygenation, optimal management of mechanical ventilation remains indispensable, and the impact of gas exchange depends on a complex interplay of ECMO blood and gas flows, native lung and cardiac function as well as the mechanical ventilation strategy applied.[46] In general, minute ventilation during V-A ECMO support has to be decreased due to the CO_2 removal by ECMO to avoid hypocapnia. After stabilization, early extubation is advised to avoid complications such as ventilator-associated pneumonia or need for tracheostomy.[47]

Table 2 Most frequently used sedative, vasoactive drugs, and anticoagulation in percutaneous ventricular assist devices supported patients

Drug	T½	Dosage	CO	SVR	Heart rate	Comment and experience during pVAD support
Sedation						
Propofol	0.5–1 h	0.5–4 mg/kg/h	↓	↓↓↓	↓	Often first-line sedation during pVAD support lowers preload and attenuates sympathetic tone. Has been associated with impaired oxygenator function but observational studies fail to confirm this compared to midazolam.[17]
Midazolam	1.5–2.5 h	0,03–0,2 mg/kg/h	→	↓	↓	Accumulates with time leading to prolonged sedation, observational data in pVAD.
Dexmedetomidine	Up to 4 h	0,2–1,4 µg/kg/min	↓	↓	↓↓	Selective α2-receptor agonist, no data in pVAD.
Fentanyl	Up to 6 h	0,5–2,0 µg/kg/min	→	→	↓	Opioid agonist 100 × as potent than morphine, no data in pVAD but widely used.
Remifentanil	3–10 min	0,5–1 µg/kg/min	→	→	↓	Opioid agonist, a single observational study suggests increased clearance in patients on V-A ECMO.[18]
Inotrope						
Dobutamine	2–5 min	2–10 µg/kg/min	↑↑	↓↓	↑↑	β1-Receptor agonist, empiric first choice inotrope, no controlled studies in pVAD, but well suited due to short half-life.
Milrinone	2–3 h	0.375–0.75 µg/kg/min	↑↑	↓↓↓	↑	Phosphodiesterase-3 inhibitor, not superior or inferior to dobutamine in CS,[19] accumulates in renal failure, no controlled data in pVAD.
Levosimendan	1–2 h for levosimendan and 70–80 h for active metabolites	0.05–0.2 µg/kg/min	↑↑	↓↓	↑↑	Due to long T½ of active metabolites not a first-line drug in CS and no controlled trials have investigated the drug in CS. Observational data are mixed whether levosimendan facilitates V-A ECMO weaning.[20,21]
Vasopressor						
Norepinephrine	2–5 min	0.01–0.50 µg/kg/min	↑	↑↑↑	↑	First-line vasopressor to increase perfusion pressure. Is frequently used but no controlled pVAD studies.
Dopamine	2–5 min	5–10 µg/kg/min	↑–↑↑	↑	↑↑↑	Not first-line drug, increases risk of arrhythmia and mortality[19] especially in dosage >10 µg/kg/min. No human data in pVAD. Animal data suggest no benefit compared to norepinephrine during Impella® CP support.[22]
Epinephrine	2–5 min	0.01–0.50 µg/kg/min	↑↑↑	↑↑↑	↑↑↑	Potent catecholamine, causes increased aerobic glycolysis (elevated lactate). The RCT in CS suggests harm[23,24] that also has been seen in observational data in pVAD.[25]
Vasopressin	6–30 min	0.01–0.04 IU/min	→	↑↑↑	→	Potent vasoconstrictor, not first-line. Increases risk of intestine ischaemia. No controlled data in pVAD but animal study favours vasopressin over norepinephrine during V-A ECMO.[26]
Anticoagulation						
Heparin	40–150 min	Titrated to APTT/ ACT/factor X_a target	→	→	→	First-line anticoagulation, usually dosage titrated to APTT/X_a target. Heparin should be deferred in case of bleeding. No RCT data on higher vs. lower APTT target in pVAD.
Argatroban	60 min	Titrated to APTT/ ACT	→	→	→	Selective thrombin inhibitor alternative to heparin. Accumulates in renal dysfunction

ACT, activated clotting time; APTT, activated partial thromboplastin clotting time; CO, cardiac output; h, hour; RCT, randomized clinical trial; SVR, systemic vascular resistance; T½, plasma half-life.

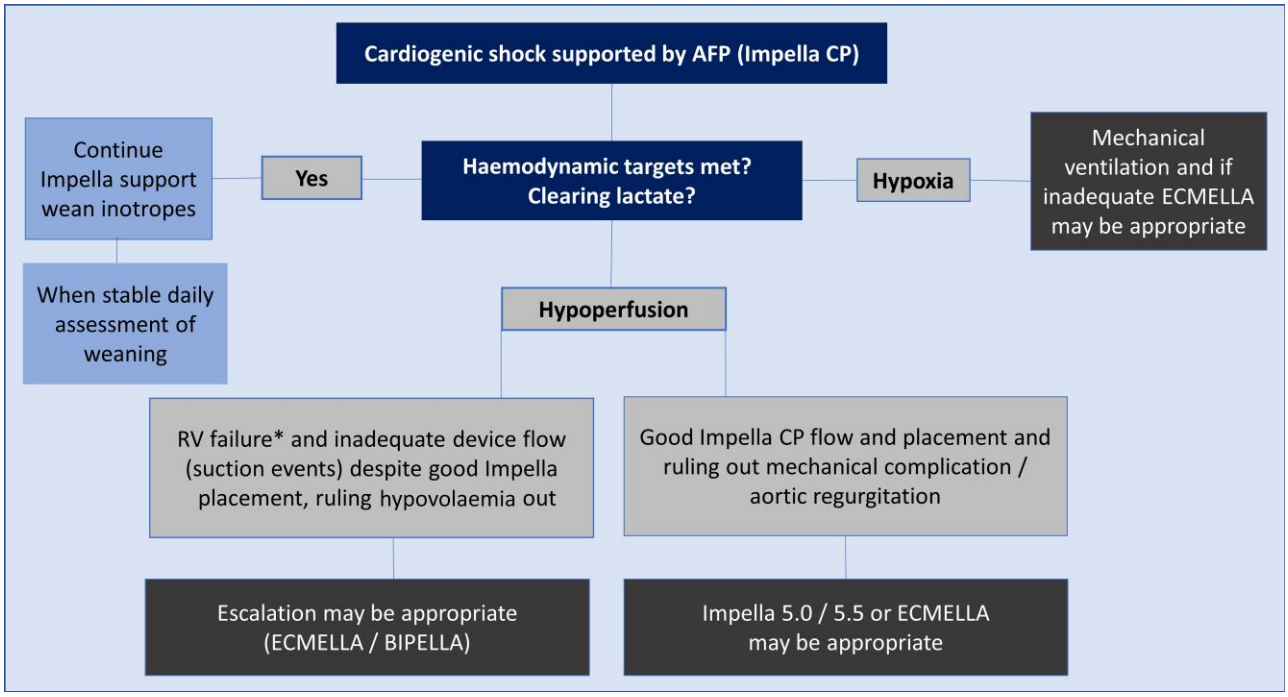
Cardiogenic shock supported by AFP (Impella CP)
Haemodynamic targets met? Clearing lactate?
Yes
Continue Impella support wean inotropes
When stable daily assessment of weaning
Hypoxia
Mechanical ventilation and if inadequate ECMELLA may be appropriate
Hypoperfusion
RV failure* and inadequate device flow (suction events) despite good Impella placement, ruling hypovolaemia out
Good Impella CP flow and placement and ruling out mechanical complication / aortic regurgitation
Escalation may be appropriate (ECMELLA / BIPELLA)
Impella 5.0 / 5.5 or ECMELLA may be appropriate

Figure 2 Flowchart to identify and handle potential need for escalation of mechanical circulatory support in patients supported by axial flow pump (AFP). See text for details. The use of BIPELLA (combination of right- and left-sided AFPs) requires adequate oxygenation. ECMELLA, combination of veno-arterial extracorporeal membrane oxygenation and AFP. AFP, supported by axial flow pump.

In case of lung failure, deoxygenated blood may be ejected from the heart supplying the coronary arteries and brain causing regional hypoxia. This situation is termed differential hypoxaemia, Harlequin phenomena, or North-South Syndrome.[12] This should be addressed by optimizing ventilatory settings and, if insufficient, a Veno - Artetiral Venous (V-AV) ECMO configuration might be appropriate. In case of cardiorespiratory failure, where cardiac function has recovered, but the lungs remain severely impaired, configuration change to Veno - Venous (V-V) ECMO may be an option.

Renal replacement therapy

Acute kidney injury (AKI) occurs in up to one half of patients with CS, and 20% of these will require renal replacement therapy (RRT). In patients on pVAD support, the need for RRT has been shown to be considerably higher.[48] The AKI is a strong predictor of poor outcomes and is associated with a two-fold increase in the risk of in-hospital mortality if requiring RRT.[49] To date, there are no controlled trials assessing optimal timing of RRT in CS, and thus, no clear recommendation exists for the ideal timing for RRT that usually follows general recommendations in critically ill patients.[50] But the fact that patients supported by pVAD poorly tolerate acute fluid shifts makes continuous RRT advisable. The V-A ECMO allows the RRT system to be connected directly to the ECMO circuit thereby avoiding placement of an additional dialysis catheter although whether this increases the risk of systemic emboli is unknown.

Neurological prognostication

Many patients supported by pVAD suffer from hypoxic brain injury after cardiac arrest or a cerebral embolus/haemorrhage and subsequently die in persistent coma after withdrawal of life-sustaining treatment.[2] Systematic neuroprognostication is essential,[51,52] which includes clinical evaluation, electrophysiology [electroencephalogram (EEG) and in selected cases, somatosensory-evoked potentials (SSEP)], imaging (CT as MRI is not possible while on pVAD), and biomarkers [neuron specific enolase (NSE) and neurofilament].[53,54] Malignant prognostic signs include irreversible coma,[55] absent pupillary and/or corneal reflex, early myoclonus or seizures, unreactive EEG background, epileptiform EEG, bilaterally absent cortical SSEPs, and high NSE values at 48 and 72 h.[54,56] These signs are more uncertain in pVAD supported patients where time to awakening after resuscitation is highly variable especially in refractory arrest.[57] The NSE may be used[58,59] but haemolysis may lead to high NSE unrelated to brain injury. A multimodal neuroprognostication strategy is advised.[51,52] Decisions about withdrawal of life-sustaining therapy should be considered in addition to brain injury in all aspects such as age, comorbidities, organ failure and the implications for individual end-of-life wishes.

Practical management of a percutaneous ventricular assist devices patient: what to expect during the first 24 h

Volume management

During the first hours of pVAD support, a vasodilatory state often develops. Relative hypovolaemia may require administration of fluids for restoring volume status and reduce pump speed to avoid suction events. The lowest central venous pressure associated with haemodynamic stability and pump function should be targeted and haematocrit should be >0.24, *Table 1*.

Monitoring systemic perfusion and blood flow

In patients supported on V-A ECMO, blood flow should be reduced after systemic perfusion is restored, to allow intracardiac flow and

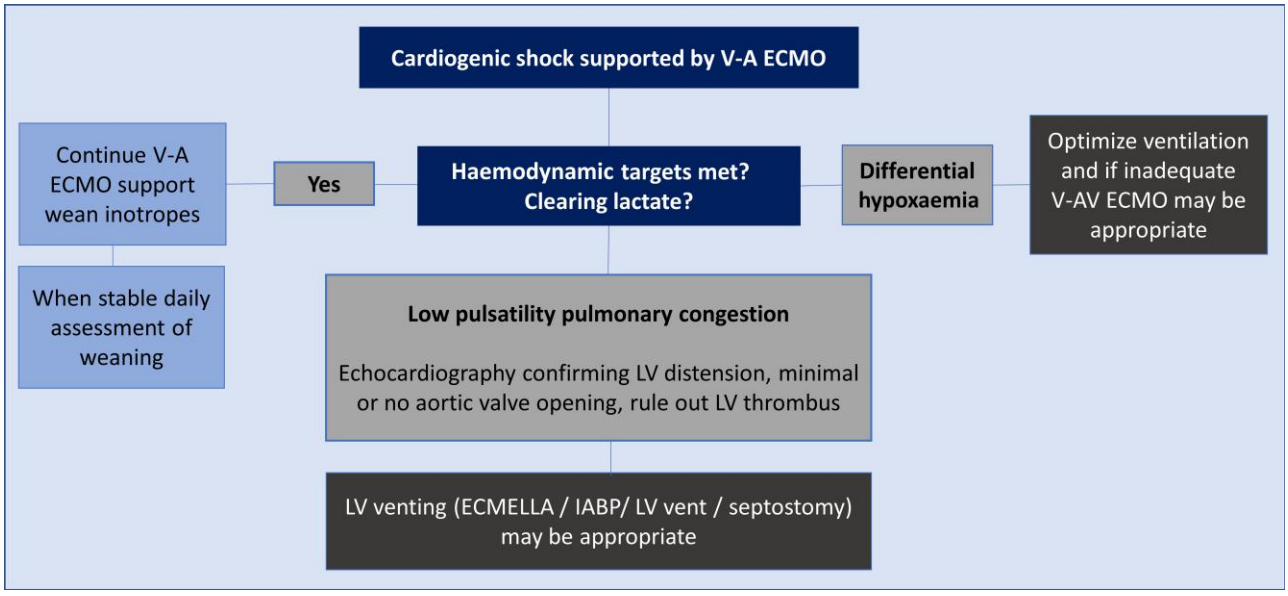
Cardiogenic shock supported by V-A ECMO
Continue V-A ECMO support wean inotropes
Yes
Haemodynamic targets met? Clearing lactate?
Differential hypoxaemia
Optimize ventilation and if inadequate V-AV ECMO may be appropriate
When stable daily assessment of weaning
Low pulsatility pulmonary congestion
Echocardiography confirming LV distension, minimal or no aortic valve opening, rule out LV thrombus
LV venting (ECMELLA / IABP/ LV vent / septostomy) may be appropriate

Figure 3 Flowchart to identify and handle potential need for venting during veno-arterial extracorporeal membrane oxygenation (V-A ECMO support). LV, left ventricular; IABP, intra-aortic balloon pump; ECMELLA, combination of V-A ECMO and axial flow pump; V-A ECMO, veno-arterial extracorporeal membrane oxygenation.

aortic valve opening thus reducing the risk of intraventricular thrombi[60] and reduce the risk of pulmonary congestion. In patients supported by AFP, the flow should be increased as much as possible avoiding suction events and haemolysis. Monitoring of lactate and lactate clearance is particularly important in the early phase. In case of inadequate flow (persistently high or increasing lactate) despite running well on high performance level, escalation to a more powerful axial flow device (Impella® 5.0 or 5.5) or adding V-A ECMO (ECMELLA) may be appropriate (*Figure 2*). All patients on pVAD using femoral access, limb perfusion is advised to be monitored using arterial Doppler, temperature of the limb, also, near-infrared spektroskopi (NIRS) may be useful to detect signs of limb ischaemia.[61] With tMCS and especially AFP, the erythrocyte shear stress generated by flow through the extracorporeal circuit or AFP can induce erythrocyte lysis and release free haemoglobin.[62] Haemolysis is advised monitored with measurement of plasma free haemoglobin. During AFP support, haemolysis is most likely the result of malposition of the device, and echocardiography is advised to be done to optimize placement, and flow should be reduced until haemolysis is resolved.

Intravenous vasoactive drugs

It is advised to use these drugs at the lowest dose needed and to rapidly reduce and stop infusion when systemic perfusion has been restored, *Table 2*.

Managing bleeding and haemostasis

Balancing the risks between bleeding and thrombosis is one of the main clinical challenges in these patients. During the first hours of support, bleeding risk usually outweighs thrombotic risk, and systemic anticoagulation can be minimized or deferred. The lack of high-quality data to guide anticoagulation management in V-A ECMO-treated patients results in marked practice variability among centres.[63] Potential modulation of dual antiplatelet therapy during a bleeding episode should always be weighed against risk of stent thrombosis and should be discussed with the percutaneous coronary intervention operator.

Practical management of a percutaneous ventricular assist devices patient: what to expect after the first 24 h and up to 72 h

Volume management and sedation

Systemic inflammation and vasodilation may still be present, and the same treatment goals should be used as in the initial 24 h. Excessive fluid loading should nevertheless be avoided. Femoral placed pVAD especially AFP are sensitive to patient movement and usually will require some sedation.

Monitoring systemic perfusion and pump flow

Maintenance of sinus rhythm and avoidance of tachycardia should actively be pursued to improve performance of support systems and reduce myocardial oxygen consumption. In case of suction events and haemolysis, echocardiography should be performed immediately to re-evaluate appropriate AFP placement, RV function, and volume status. Low pulsatility or complete decoupling between LV and aortic pressure with AFPs should prompt close surveillance of lactate, urine output, and SVO_2 to detect signs of hypoperfusion. In case of hypoperfusion due to low cardiac output despite adequate volume status, inotropic stimulation should be attempted before escalating to more powerful devices (Impella® 5.0 or 5.5 or V-A ECMO) (*Figure 2*).

In patients supported by V-A ECMO, blood flow should be individualized to secure adequate organ perfusion and to allow LV ejection. Echocardiography is advised daily to evaluate LV ejection, signs of LV thrombus, and recovery of native heart function. In case of low pulsatility and distention of the LV, LV venting is advised, *Figure 3*. Venting is commonly done using combination of AFP and V-A ECMO (ECMELLA) or combination of IABP and V-A ECMO. In ECMELLA, the LV is unloaded effectively ameliorating LV distention and has the potential to transition from V-A ECMO to AFP support alone. The IABP will aid aorta valve opening by reducing afterload during ejection. Other methods such as surgical vents and atrial

Table 3 Most frequently reported variables associated with higher likelihood of weaning from pVAD

Variable	Value	Comment and experience in MCS
Echocardiography		
LVOT VTI	>10–12 cm	Is a measure of native heart stroke volume. Observational studies suggest that a value >10 cm is associated with increased likelihood of weaning success. Measure is based on PW Doppler, thus, angle dependent between flow direction and Doppler cursor, further load dependent at affected by aortic regurgitation. Only data in V-A ECMO supported patients.[68,69]
LVEF	>25% or increase >5% within 48 h	Measure of total LV stroke volume relative to end-diastolic volume. Value >20–25% associated with higher likelihood of weaning success. Mitral regurgitation will overestimate forward flow, load dependent and heavily dependent on good image quality. Only data in V-A ECMO supported patients.[68,69]
TDI S'_{lat}	>6 cm/s	Tissue Doppler measurement of velocity of myocardial movement. Doppler cursor placed in lateral mitral annulus will provide information on LV systolic function and diastolic using e′. Angle dependent and cannot differentiate between active and passive movements. Only data in V-A ECMO supported patients.[68–70]
Other		
EtCO2	Increase >5 mmHg	Measure of flow through the lungs thus intrinsic heart function in V-A ECMO supported patients. An increase >5 mmHg measured 12 h apart suggest likelihood of weaning. Subject to ventilator settings. Only data in V-A ECMO supported patients and in axial flow pump supported patients EtCO2 will be sum of device flow and intrinsic heart function.[71]

EtCO2, end tidal CO_2; LVOT, left ventricular outflow tract; LVEF, left ventricular ejection fraction; TDI, tissue Doppler imaging; VTI, velocity time integral.

septostomy can also be used. There are still no solid evidence beside retrospective cohort studies and propensity matched analyses to support this, and addition of an unloading device may increase the risk of complications.[64,65] There are ongoing randomized trials evaluating the effect of these strategies on all-cause mortality (ClinicalTrials.gov NCT05577195). Systemic oxygenation in upper body should be monitored closely to detect differential hypoxaemia after LV venting is started.

Practical management of a percutaneous ventricular assist devices patient: what to expect after 72 h and weaning

An early weaning strategy is advised once the signs of myocardial recovery during reduction of pVAD flow occur. Several features may predict the likelihood of myocardial recovery including age, underlying pathology, and presence/absence of pulmonary hypertension.[66] Doppler echocardiographic LV outflow velocity time integral >10–12 cm is the most widely used parameter to track LV recovery in patients on V-A ECMO, also, lateral S wave >6 cm/s has been suggested as predictors of myocardial recovery and successful weaning.[66]

Sometimes, weaning can be facilitated by using pharmacological unloading strategies to reduce afterload, reduce preload, or increase contractility. Observational data suggested that levosimendan may increase the likelihood of successful ECMO weaning,[20] but opposite results have also been reported.[21] More definitive data will come after completion of an ongoing randomized trial.[67] In case of unsuccessful weaning, it is vital to identify and address the cause of weaning failure.

If weaning continues to fail, following options might be appropriate: longer run on the existing device; transition to another pVAD with the possibility of mobilising the patient (axillary AFP) if cardiac recovery is anticipated; upgrade to more durable circulatory support; or palliation and withdrawal of support. This decision is especially important in patients with end-stage cardiomyopathy with low likelihood of recovery and should be undertaken by a multidisciplinary team (cardiogenic shock team).

Complications and trouble shooting

Percutaneous ventricular assist devices carry a high risk of device-associated or device-induced complications in particular because of the large lumen cannulas (*Table 4*).

Veno-arterial extracorporeal membrane oxygenation

Cannula site bleeding is the most frequent V-A ECMO associated complication requiring surgical or interventional revision in up to 42%.[74] The concominant occurrence of coagulopathy due to systemic anticoagulation, device-related haemolysis, or thrombocytopaenia and injury of the cannulated vessels may cause the bleeding.[74,75] Besides interventional or surgical revision, cannula site bleeding may be diminished and controlled by local compression. In case of uncontrolled bleeding, an alternative access might be indicated or device-support interrupted. In case of coagulopathy, transfusion of clotting factors or thrombocytes is subsidiary.[75] The V-A ECMO-related haemolysis is relatively common[75] but usually mild and transient in comparison to higher speed devices such as the Impella®. Haemolysis might be decreased by cannula re-positioning or blood flow adjustment with respect to patient's haemodynamics. Haemolysis during AFP support often indicates misplacement of the device.

Limb ischaemia is another serious complication that in case of subsequent compartment syndrome may require fasciotomy in up to 10% of ECMO patients and limb amputation in up to 5%.[76] The risk of limb ischaemia may usually be reduced by an additional antegrade perfusion cannula, which is advised in most V-A ECMO patients with femoral cannulation. Limb ischaemia can also be caused by potentially distally migrating clot formation at the cannulation site. A feasible approach to prevent distal limb ischaemia by interventional removal has recently been described by Sulimov *et al.*[77] Future studies should also assess effect of newer generation bi-flow cannulas.

Axial flow pump

In general, Impella® CP is inserted percutaneously using the common femoral artery. Bleeding complications are common (up to 54%)[78] related to large lumen access, systemic anticoagulation, and thrombocyte

Table 4 Most frequent complications related to veno-arterial extracorporeal membrane oxygenation and axial flow pump[6,72,73]

	V-A ECMO	Axial flow pump
Very frequent (>10%)	Cannulation site bleeding Haemolysis (often mild transient) Limb ischaemia LV distension pulmonary congestion Sepsis	Cannulation site bleeding Haemolysis (often mild transient) Sepsis Suction events
Frequent (2–10%)	Stroke Harlequin phenomenon Cardiac tamponade	Stroke Limb ischaemia
Infrequent <2%	Amputation due to limb ischaemia Technical device failure Pulmonary haemorrhage	Amputation due to limb ischaemia Technical device failure Damage to aortic or mitral valve

damage or haemolysis caused by pump-related shear stress (7–8%).[79] The incidence of limb ischaemia is less frequent than in V-A ECMO patients (due to smaller lumen of introducer) and ranges from 0.07% to 10%.[76] Problem-solving strategies are similar to those described in V-A ECMO although the system does not allow placement of antegrade limb perfusion cannula. Prevention and management strategies to reduce peripheral complications of pVAD have recently been summarized by an expert consensus group.[80]

Conclusion

The use of pVAD has increased rapidly during the last decade without substantial evidence for their effect on outcome. Even though the upcoming results of event-driven studies investigating general use of V-A ECMO[7] and Impella® CP[8] in AMI-CS will provide pivotal insight into the general use of pVAD, many gaps in knowledge still exist such as the optimal timing of placement and duration of support, management of complications, concomitant medical therapies, and weaning. In patients with refractory cardiac arrest and SCAI class D and E shock, pVAD have an important role. The pVAD are associated with complications, and their use requires substantial experience. Centralization in expert centres and shock team approach can both optimize the benefit risk ratio of pVAD use.

Supplementary material

Supplementary material is available at *European Heart Journal: Acute Cardiovascular Care* online.

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Data availability

No new data were generated or analysed in support of this research.

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